CONTROLLING THE ADHESION FORCE FOR ELECTROSTATIC ACTUATION OF MICROSCALE MERCURY DROP BY PHYSICAL SURFACE MODIFICATION

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ABSTRACT

Under electrostatic actuation, mercury droplet can act as a contact and moving part in a microswitch system. In order to reduce the actuation voltage while keeping the electrical advantages of liquid-solid contact, the contact properties of mercury droplet on structured surfaces are investigated in this paper. Forces to actuate a mercury droplet on different structured surfaces are theoretically analyzed and experimentally tested. Both results confirm our claim that the adhesion forces of liquid metal droplets on a solid surface can be designed by physical modification of the surface. The criteria for detaching a mercury droplet from solid surface was predicted and verified by experimental results.

INTRODUCTION

This paper reports that adhesion forces of liquid droplets on solid surfaces can be *designed* by physical surface modification (as opposed to chemical treatment). For solid-to-solid contact, it is well known that the effective adhesion force is reduced on rough surface. We expect a similar condition for liquid metals on a solid surface. Our approach to *design* this adhesion force is to control the contact surface area between droplet and a solid surface by micromachining the solid surface.

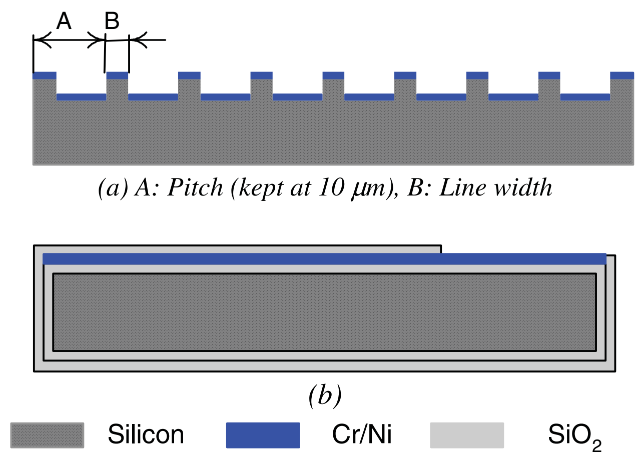
We first develop theoretical understanding of the phenomena through mechanical analysis and contact angle measurements on simple structured surfaces. The knowledge is then applied to two different modes of electrostatic actuation of a mercury droplet – sliding on and detaching from the surface.

Mercury microswitching, where a mercury droplet acts as the moving and contact part, is an excellent candidate to benefit from this surface modification. The liquid-to-solid electrical contact brings significant advantages over conventional MEMS switch [1-4] with solid-to-solid contact, such as lower contact resistance, and lower contact surfaces degradation. There are two main reasons to use this kind of surface modification in mercury microswitching system. First, chemical modification of electrode surface needs to be avoided so that the contact resistance between mercury and electrode pad is not compromised. Second, thanks to the high surface tension and non-wetting nature of mercury, the surface modification can be made with even usual lithographic micromachining.

We have demonstrated various droplet-based microswitches in the past [5-8]. In microscale, the strong adhesion of droplets provides the stability against disturbances and makes the switch naturally bistable. However, relatively large forces are needed to actuate the droplets against adhesion. Since adhesion keeps mercury droplets in place even at tens of thousands of G's in microscale, reducing the adhesion is acceptable and perhaps the only way to reduce the driving voltage. This paper will present a set of experimental and theoretical results of controlling adhesion force by physical surface modification.

SAMPLE PREPARATION

We employed simple line patterns for surface modification, made by DRIE, to keep the analysis manageable. A series of line patterns, shown in Fig. 1(a), are made with contact ratio (i.e., line width per pitch, which is B/A) ranging from 0.3 to 0.7, while keeping the pitch at 10 µm. After DRIE, a 2000Å thin Cr/Ni layer is deposited on this line-patterned surface to ensure good electric conductivity during testing.



(a) A: Pitch (kept at 10 µm), B: Line width

(b)

Fig. 1 Testing samples (a) Surface-patterned wafer (b) Actuation wafer

Another wafer needed to conduct testing is the actuation wafer, where the high voltage is applied to attract the mercury placed on the line-patterned wafer. A thermal oxide layer is grown on silicon wafer. A layer of Cr/Ni (2000 Å) is then deposited on top of this silicon dioxide. Final oxide layer is deposited on the nickel surface by PECVD to prevent electrical shorting in case the liquid metal droplet touches both actuation wafer and surface wafer. Finally, part of PECVD oxide is removed by HF to make opening for electrical contact, as shown in Fig. 1(b).

FORCE ANALYSIS

By using a high performance goniometer (First Ten Angstrom FTA4000), apparent contact angles of mercury droplet on controlled sample surfaces can be measured. As contact ratio B/A decreases, we confirm that apparent contact angle of mercury droplet increases (Fig. 2), and the apparent contact area of droplet decreases (Fig. 3), suggesting us that the adhesion force will decrease.

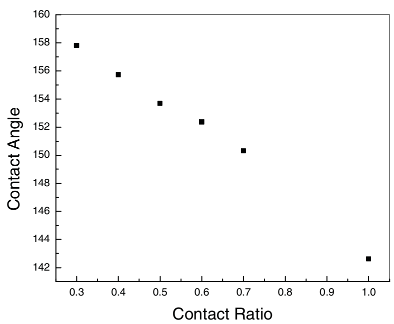
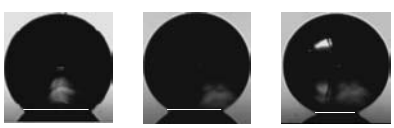


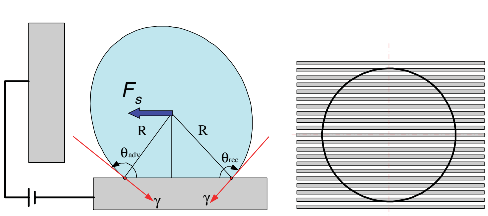
Fig. 2 Contact angles of mercury droplet on different surfaces



Non-pattern 0.7 contact ratio 0.3 contact ratio

Fig. 3 Apparent contact area of mercury droplet on different surfaces

For sliding, a drive electrode is placed laterally near the droplet and pulls it parallel to the surface. The actuation force needs to overcome the resistant force due to the hysteresis of contact angle, shown in Fig. 4



(a) (b)

Fig. 4 Sliding a droplet on a solid surface (a) cross-section view (b) contact area

$$F_s = \gamma L\cos(\pi - \theta_{adv}) - \gamma L\cos(\pi - \theta_{rec}) \qquad (1)$$

where γ: the mercury/air surface tension

L: the effective contact length between mercury droplet and solid surface, which can be expressed as $L = \eta \cdot 2R\cos(\theta - \frac{\pi}{2})$, η : contact ratio

θ_{adv} and θ_{rec}: advancing and receding contact angle

The contact angle hysteresis is small enough for us to reasonably assume that

$$\theta_{adv} = \theta + \frac{1}{2}\Delta\theta; \quad \theta_{rec} = \theta - \frac{1}{2}\Delta\theta$$

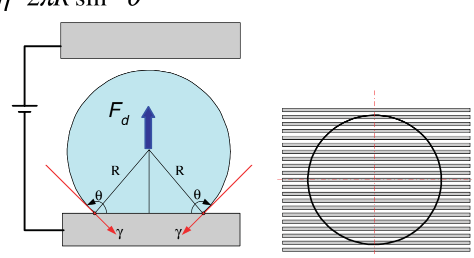
So the force in Eqn. 1 can be expressed as

$$F_s = \gamma\eta \cdot 4R\sin^2\theta\sin(\frac{1}{2}\Delta\theta) \qquad (2)$$

where θ is contact angle of mercury, which is related to contact ratio η, and $\Delta\theta$ is contact angle hysteresis.

For a droplet detaching, a driving electrode is placed parallel above the droplet to pull and detach it from a solid surface (Fig 5), the actuation force needs to overcome the surface tension. This force can be expressed as

$$F_d = \gamma\eta \cdot 2\pi R\sin^2\theta \qquad (3)$$



(a) (b)

Fig. 5 Detaching a droplet from a solid surface (a) cross-section view (b) contact area

By comparing these forces, we can see that the force to slide a droplet on a surface is smaller than the force to detach a droplet from a surface by a factor of $\frac{2}{\pi}\sin(\frac{1}{2}\Delta\theta)$.

Combing with the contact angle data on surfaces with different contact ratio, shown in Fig. 2, we can get relative force on surfaces with different contact ratio from Eqn. (2) and Eqn. (3). Fig. 6 predicts the force on microstructured surfaces relative to the actuation force on flat surface (η=1)

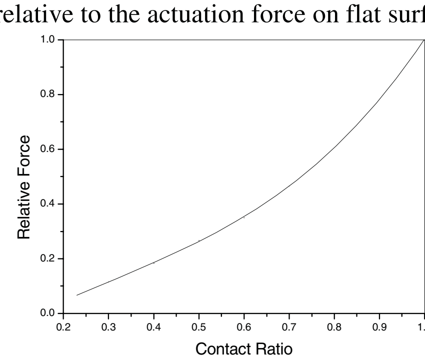


Fig. 6 Predicted trend of the adhesion force on various contact surfaces relative to the one on flat surface

ACTUATION EXPERIMENTS AND RESULTS

During sliding testing, a CCD and microscopy system is used to monitor and record the behavior of liquid metal droplet under experiment. Table 1 is the testing result of sliding a droplet of 550 µm on microstructured surfaces with the initial gap between the mercury surface and driving electrode as 20 µm.

Table 1 Actuation voltage to slide a droplet on microstructured surfaces

Contact ratio	Driving voltage (V)	Relative driving voltage	Relative force
0.3	42	0.37	0.14
0.4	49	0.43	0.18
0.5	62	0.54	0.29
0.6	70	0.61	0.37
0.7	77	0.67	0.45
1	115	1	1

Because electrostatic force is proportional to the voltage square, we can get the relative force on each surface. If we plot these data into the theoretic curve in Fig. 6, we can see that the data follows the theoretic curve very well, as shown in Fig 7. The adhesion force on patterned surface with 0.3 contact ratio is only about 10% of that on flat (i.e., non-patterned) surface, confirming our claim that adhesion of surface can be designed by lithography.

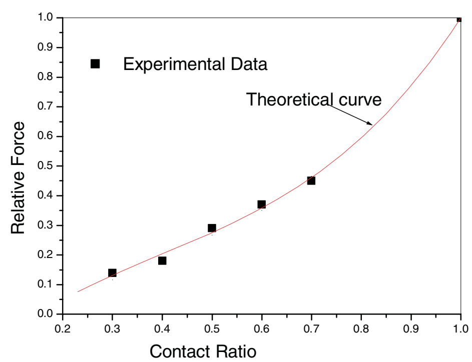
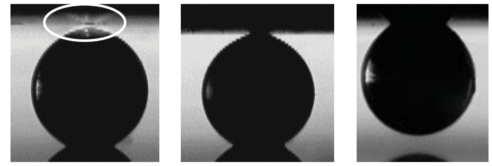


Fig. 7 Sliding test results fit with predicted curve

For detaching, a drive electrode is placed horizontally above the droplet and pulls it up. The resistance against detaching is expected higher than that of against sliding, as the detachment process requires creating new free surfaces [9]. As a higher voltage is applied, electric breakdown may occur (Fig. 8a). Furthermore, the droplet may deform enough to contact both electrodes under electrostatic actuation (Fig. 8b). These two adverse effects must be considered to find out the criteria for detaching mercury droplet.



(a) (b) (c)

Fig. 8: Detaching experiment. (a) Electric breakdown, (b) Bridging, and (c) Detaching during detach testing

CRITERIA FOR DETACHING

Because our system is in microscale, we can estimate the breakdown voltages for each gap by Paschen curve. At the same time, our testing conditions such as air pressure, humidity, temperature, etc, will make the breakdown curve deviate from Paschen curve. The actual breakdown curve is obtained experimentally and included in Fig. 9. To successfully detach a droplet from solid surface, the critical voltage cannot be larger than the breakdown voltage.

The droplet under electrostatic actuation will deform before it is moved. For the sliding case, this deformation effect leads to the contact angle hysteresis ($\Delta\theta \sim 5^o$). Considering the contact angle θ is 142^o and contact angle hysteresis is 5^o, we can convert this contact angle hysteresis to the droplet's deformation as: $\Delta l = 0.035 \cdot R$, where R is the radius of the droplet.

For the detaching case, the droplet deformation may cause the bridge effect. Based on Eqn. (2) and Eqn. (3), the force to detach a droplet is about 35 times larger than the force to slide a droplet on the same surface, so we can reasonably assume that the deformation for detaching case is 35 times larger than that of the sliding case. We can estimate the maximal droplet sizes allowed for detaching on a given surface with different actuation gaps. Table 2 shows the analysis results for detach on a microstructure surface with 0.3 contact ratio.

Table 2: Critical droplet size for each actuation gap

Actuation Gap (µm)	10	20	30	40
Critical Radius (µm)	60	120	180	240

For the case of sliding a droplet on a flat surface with a given actuation gap, the driving voltage was found to decrease with the increase of droplet size [8]. We can expect the same trend of driving voltage for the case of detaching. So each maximum droplet size in the Table 2 for a given gap represents the minimum voltage needed to avoid bridging effect. Based on these analytical data, we can plot the bridging line in Fig. 9. The criteria in Fig. 9 clearly indicate that detachment can occur only between these two lines.

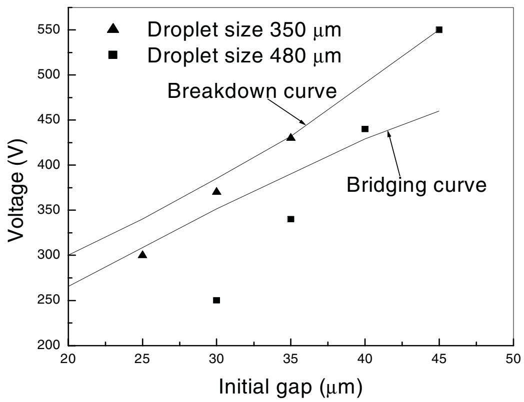


Fig. 9 Criteria for detaching a droplet (breakdown curve and bridging curve) on a surface with 0.3 contact ratio and experimental data

To verify these detaching criteria, the goniometer (First Ten Angstrom FTA4000), mainly used to measure the contact angle of microscopic liquid droplets, is again used to test the detaching voltage. This system can take live video of actuation through a side camera and allows precise control of the gap by a stepping motor. Table 3 is the experimental result of detaching test.

Table 3 Detaching test data for droplets on a surface with 0.3 contact ratio

Droplet Diameter (μm)	Gap (μm)	Bridging (V)	Detaching (V)	Breakdown (V)
350	25	300		
350	30		370	
350	35			430
480	30	250		
480	35	340		
480	40		440	
480	45			550

Including these data into Fig. 9, we can see that all the detachment data locate between two criteria lines, while all the bridging voltages locate below the bridging curve.

CONCLUSION

We have analyzed the forces to slide and detach a liquid metal droplet on micromachined surfaces. The trend of relative force on different surfaces has been theoretically obtained. The effect of microstrcuctured surface has been evaluated. Testing results confirm our claim that the adhesion between liquid metal and solid surface can be designed by lithography. Finally, the criteria for droplet detachment was analyzed and experimentally verified. From analytical and experimental results, we can see that we can control the adhesion force by controlling the contact ratio between droplet and solid surface. These results provide a good understanding in designing a mercury microswitching system with lower driving voltage. In order to decrease driving voltage, the microstructured patterns can be made on solid surface of switch cells to reasonably reduce the adhesion without losing the advantage of liquid contact such as bistable operation, low contact resistance.

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